Economics of gas to wire technology applied in gas flare management

Ojijiagwo, E. , Oduoza, C. F. and Emekwuru, N.

Original citation:
Ojijiagwo, E. , Oduoza, C. F. and Emekwuru, N. (2016) Economics of gas to wire technology applied in gas flare management . Engineering Science and Technology, an International Journal, volume (in press)

http://dx.doi.org/10.1016/j.jestch.2016.09.012

DOI: 10.1016/j.jestch.2016.09.012
ISSN: 2215-0986

Publisher: Elsevier

Engineering Science and Technology, an International Journal xxx (2016) xxx–xxx

HOSTED BY

ELSEVIER

Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: www.elsevier.com/locate/jestch

Full Length Article

Economics of gas to wire technology applied in gas flare management

Emeka Ojijiagwo [a,*], Chike F. Oduoza [a], Nwabueze Emekwuru [b]

[a] Faculty of Science and Engineering, University of Wolverhampton, WV1 1LY Wolverhampton, United Kingdom
[b] Faculty of Engineering, Coventry University, CV1 5FB Coventry, United Kingdom

ARTICLE INFO

Article history:
Received 18 August 2016
Revised 15 September 2016
Accepted 15 September 2016
Available online xxxx

Keywords:
Gas flare reduction
Gas-to-wire technology
Economic valuation
Power generation

ABSTRACT

Our environment is increasingly being endangered by the introduction of greenhouse gases which are continuously produced from gas flaring processes. Currently, total volume of gas flared globally amounts to 100 billion cubic meters (BCM) annually. Nigeria flares about 18.27 BCM and loses approximately $2 billion yearly. This statistics indicates the urgent need to conduct research aimed at addressing both the environmental impact of gas flaring and the economic implications. This research studies the economic viability of using gas to wire (GTW) technology as an integral component of gas flare management. The investigation critically evaluates the cost implications and impact of the GTW technology. The research method involves the interview of key experts and practitioners in the field. The interviews are structured to obtain information on the total volume of gas produced, utilised and flared in two major gas and electricity producing firms in Nigeria. The data obtained show that the gas producing company flares about 8.33% of its total production which is in excess of the 6.6 million cubic meters (MCM) utilised daily. This study demonstrates that in the Nigerian oil and gas sector, one unit of gas turbine having 0.93 MCM gas consumption capacity generates 150 MW of electricity daily. It is found in result evaluation that 50 turbines are sufficient to consume an average of 46.5 MCM of gas daily to generate 7500 MW of electricity. Economic analysis shows that there is an annual net profit of £2.68 billion gained from flare prevention and overall environmental protection.

1. Introduction

Gas flaring occurs in the process of crude oil processing and production. About 5% of global supply of gas is wasted due to flaring and or venting as a result of lack of processing facilities, thereby causing the release of about 300 million tons of CO_2 per year into the environment [17]. This volume of flared gas could be utilised for reasonable purposes, for instance electricity generation.

According to Energy Information Administration [15], Nigeria is the 6th largest crude oil producer. It is also one of the largest producers of natural gas in the world [32]. In Nigeria, the proven natural gas reserve is currently estimated at 5.3 trillion cubic meters (187 trillion cubic feet – TCF) [1,27]. This could possibly sustain the energy needs of the Sub-Saharan Africa for several decades Ahmed et al. [1] stated that large amount of global natural gas reserves have not been used in the same ratio as petroleum crude. This could be linked to the fact that large volumes are associated gas. Regardless of all these, it still remains a vital future energy source. Ironically, despite the abundant proven natural gas reserves, Nigeria is faced with electricity generation and supply problems which are characterised by load shedding, blackouts, and reliance on private electricity generators: and these create huge economic impediment [15]. Anomohanran [5] estimated that about 47% of the total gas produced in Nigeria is practically flared; while Nwankwo and Ogogarue [29] estimated a higher percentage of about 70% as being flared from the volume of produced gas in Nigeria. The quantity of gas flared annually could be as much as 15.2 BCM [26]. Even though there are variations in the estimation of volume of flared gas, it is undeniable that huge volume of gas is flared in Nigeria, and this contributes significantly to economic waste and environmental degradation [28,34].

About 100 Billion BCM of gas is flared globally on an annual basis and gas flaring continues to pose significant threats to the environment and economy of oil and gas producing countries, therefore it is vital for this global challenge to be addressed. This research presents the GTW technology as a vital and viable management system for the excessive waste of gas. This requires systematic gathering of potential flared gas and subsequent utilisation as fuel for gas turbines for the generation of electricity. The study also establishes the economics of gas to wire technology

* Corresponding author.
E-mail address: Ojijiagwo@yahoo.com (E. Ojijiagwo).

Peer review under responsibility of Karabuk University.

http://dx.doi.org/10.1016/j.jestch.2016.09.012
2215-0986/© 2016 Karabuk University. Publishing services by Elsevier B.V.

in reducing gas flaring in Nigeria. This encompasses carrying out a cost and effect analysis on GTW technology.

1.1. Gas reserves, production and utilisation

The global availability of natural gas is valued and expected to increase with time [18]. According to BP [8], the global proven gas reserve is stated to be 185.7 trillion cubic meters and the reserve/production ration is 55.1. This has led the countries responsible for these reserves to increase production level and has also created an opportunity for increase in gas utilisation, particularly from the importers of gas. According to [8] Russia, Turkmenistan, Iran and Qatar have the highest proven reserves as shown in Fig. 1.

These four aforementioned producing countries are in possession of 58% of the entire proven gas reserves, with Russia possessing 24% and Turkmenistan having 5%. As demonstrated in Figs. 2 and 3, the Energy Information Administration has projected that by the year 2025 the natural gas consumption will almost match the production due to estimated increase of gas utilisation emanating from electricity generation. This is because natural gas is gradually becoming the fastest growing component of world primary energy. Therefore, this also validates the importance of gas to electricity as a vital means of gas utilisation. Nigeria produces 33.21 billion cubic meters (BCM) of gas yearly and utilises 14.94 BCM, which signifies that about 55% of the total annual gas production is flared.

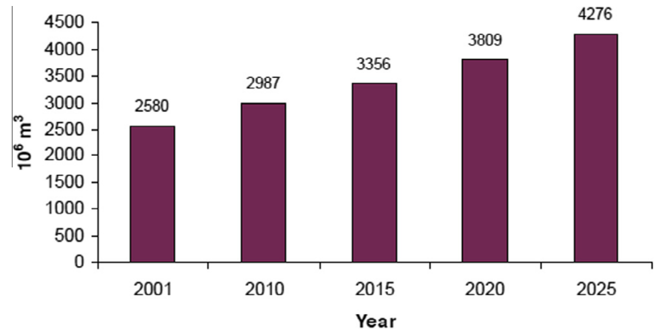

Fig. 2. Estimation of World Natural Gas Production from 2001 to 2025 [14].

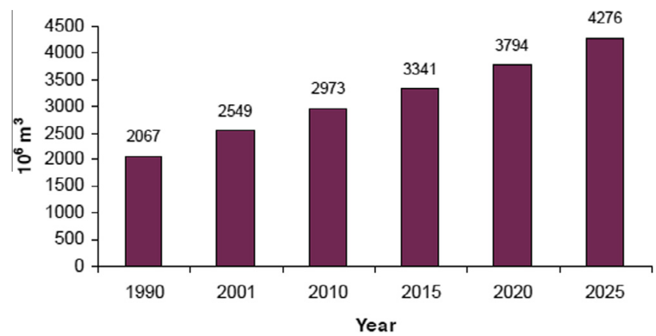

Fig. 3. Estimation of World Natural Gas Consumption from 2001 to 2025 [14].

1.2. Gas flare process

Gas flaring is referred to as a controlled system that involves the burning of gas [32], and could take place during crude oil exploration, in refineries or in chemical plants Rotty [39] identified and proposed the correlation between oil production and gas flaring and this has been in application since 1935 for the estimation of volume of flared gas Odumugbo [31] stated that there are two major options for reduction of associated gas flaring: the first is reinjection of gas into the ground for future reuse, while a second option is gas utilisation for domestic and commercial purposes, which could involve acquiring equipment for liquidification and transportation. The idea of flaring arises because it is the easiest and possibly cheaper (financially) in the short term [38].

In a lot of countries, the law prohibits gas flaring because it is harmful to the environment; although flaring could be permitted in rare cases where it is not avoidable such as in accidental breakdown of machinery and pipelines [12].

According to Oil and Gas Producers [32], gas flaring generally takes place due to the following reasons: (i) unburned process gas that results from processing, (ii) excessive gas that could not be supplied to commercial customers, (iii) vapours that are collected from the top of tanks during the filling process, (iv) production shutdown, whereby all available gas in the facility are temporarily flared to release high pressure, (v) during process upsets, maintenance and equipment changeover, and (vi) during start-up of the facility (such as olefin plants) due to safety and off-specification products.

Flared gas is made up of several compositions of which, Methane (CH_4) and Ethane have the highest mole fractions. In Table 1, the full compositions that make up flared gas are highlighted.

Fig. 4 shows the process leading to gas flaring as demonstrated by CCEI [10]. During crude oil exploration, crude oil and associated gas are produced. Crude oil is completely taken to the oil storage after treatment; while the associated gas faces two potential options – systematically gathered for utilisation or wasted through flaring. Regarding flaring, the gas is systematically channelled to the knockout drum from where gas is directed to the flare stack.

There is urgent need to manage gas flaring because the estimate by Energy Information Administration [14] predicts that annual flaring will increase by 60% from 1999 to 2020. Subsequently, it revealed that the greatest increase in gas production will emanate from Middle East (46%), seconded by Africa (18%), with the least coming from North America (3%) as shown in Fig. 5. Therefore this shows that the developing countries are highly affected by gas flar-

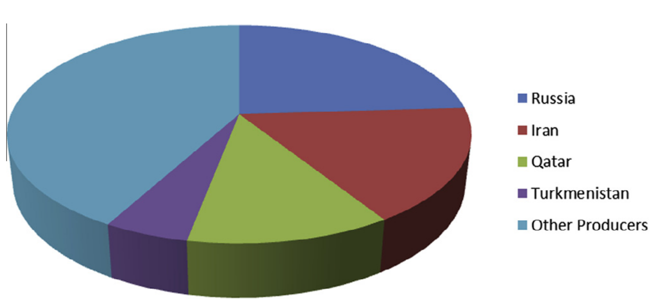

Fig. 1. Global natural gas reserves ratio [8].

Table 1
Composition of flared gas [6].

Component	Chemical formula	Volume fraction (%)	Weight fraction (%)
Methane	CH_4	81	60
Ethane	C_2H_6	5.5	7.7
Propane	C_3H_8	6.6	13.5
Butane	C_4H_{10}	4.0	10.8
Pentane	C_5H12	1.4	4.8
Nitrogen	N_2	1.0	1.3
Carbon dioxide	CO_2	0.17	0.33

Please cite this article in press as: E. Ojijiagwo et al., Economics of gas to wire technology applied in gas flare management, Eng. Sci. Tech., Int. J. (2016), http://dx.doi.org/10.1016/j.jestch.2016.09.012

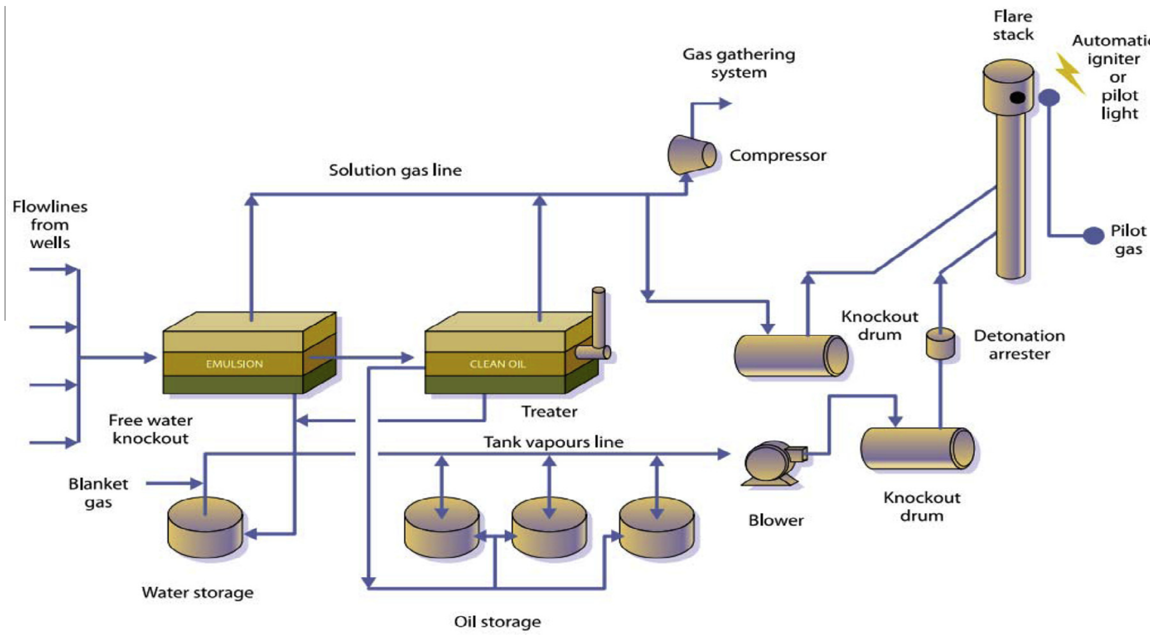

Fig. 4. Flow chart for gas production and flaring process [10].

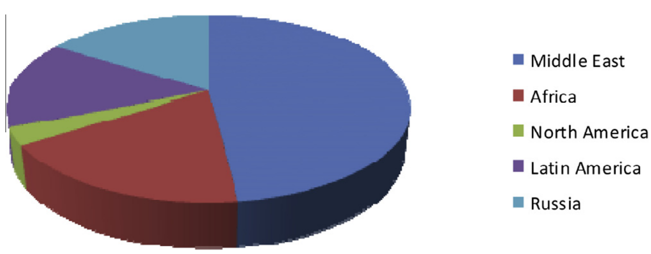

Fig. 5. Estimated future increase in gas production and flaring trends [14].

ing. However, reduction in flare volume is achievable through application of some stringent measures involving gas flaring reduction technologies.

1.3. Consequences of gas flaring

With oil production comes routine burning of the associated gas. Although in some developed societies where measures have been provided to avoid waste, the amount that is flared is minimal, but in developing societies like Nigeria, there is great concern because so much volume is still burnt. The impacts that are caused by gas flaring include environmental, economic and health and safety related.

1.3.1. Environmental impacts

Flaring of gas releases hazardous chemicals such as carcinogens and heavy metals, which negatively affect the environment. During this process, emission of carbon dioxide (CO_2) and methane (CH_4), takes place, and these potentially trigger global warming and climate change. These gases are known to have increased the average global temperature by about 0.5 degree centigrade in the last 100 years [7]. An estimated 35 million tons of carbon dioxide and 12 million tons of methane are released into the environment in the Niger Delta; surely this is astronomical and it is a major concern because of its climatic and environmental hazards. This could lead to concerns on flooding, rising sea level and tidal waves in Nigeria.

1.3.2. Acid precipitation

When sour gas is burnt, there is the production of Sulphur oxides, which are finally exposed to the atmosphere [19]. When these compounds mix up with water and oxygen, they give out an end product known as ''acid rain''. The effect of the acid rain can be toxic to the human body; it can also be experienced on the corrugated iron roofs within the flaring area – they just rust quicker now as compared with about 20–30 years ago. Steady acid into the environment creates increased pH level in the affected areas and increases the rate of extinction of flora and also make water bodies unhealthy.

There is other environmental concerns like noise pollution due to the strong sound and vibration that emanate from and during gas flaring, particularly within about 6–10 km radius of the operation [26].

1.3.3. Economic impacts

Gas flaring is a form of waste of natural resource and carries along huge economic impacts. It reduces the revenue generation. Nigeria, for instance loses about $2.5 billion annually due to gas flaring. Soil Infertility is a huge problem that is associated with gas flaring in the Niger Delta of Nigeria. Soil acidification occurs through the deposits of acids on the soil, thereby reducing the pH of the soil surface. This reduces the activities of those microorganisms that are sensitive to low pH and decreases the decomposition of plant residue and nutrients. Soil acidification also reduces plant intake of molybdate. The end product/point is that acidification of soil brings about poor farm harvests and in extreme cases brings famine. This subsequently leads to high cost of food items in the local and or national levels. It also affects the livelihood of the local farmers.

1.3.4. Health and safety

Bye products of gas flaring like carbon dioxide, nitrogen dioxide, Sulphur dioxide benzene, xylene, toluene and carcinogen compounds (dioxin and benzapyrene) have been linked with leukaemia, chronic bronchitis, asthma as well as infertility. Benzene particularly is known as one of the top 20 toxic chemicals and the exposure of the human body to benzene leads to headache,

Please cite this article in press as: E. Ojijiagwo et al., Economics of gas to wire technology applied in gas flare management, Eng. Sci. Tech., Int. J. (2016), http://dx.doi.org/10.1016/j.jestch.2016.09.012

drowsiness and can lead to death (ATSDR). Other effects associated with gas flaring at varying levels of 10–30 years are low birth weight, bone marrow damage, anaemia, decreased immune system and internal bleeding. Particularly, toluene is highly associated with severe nervous system damage. It is also reported that long exposure to moderate or even low amount can cause liver damage, as well as kidney and lungs damage; while long term exposure can even result to memory loss, vision and hearing disabilities and at the extreme death can result. In the Niger Delta, children and women are seen drying cassava and fish through the aid of the heat that comes from gas flares. Actually, it serves the locals that purpose but the irony is that as much as the goods are dried, they acquire some by-products of gas flaring like toluene, benzene, and these components are toxic to the body.

Due to the negative impacts of gas flaring, there is urgent need for a viable and economically sustainable technology to manage or minimise the volume of flared gas.

2. Review of some gas flare reduction technologies

Odumugbo [31], Indriani [14] and Thomas and Dawe [41] have demonstrated that there are existing methods for the management of gas flaring. These technologies are important because they help in reduction of adverse environmental impacts and also contribute economically. These technologies have been shown in Fig. 6 and subsequently described briefly.

2.1. Liquefied natural gas (LNG)

This is achieved after natural gas has been cooled to the temperature of approximately −162 °C and at atmospheric pressure. Development of LNG is characterised by huge financial investment in liquefaction facilities as well as LNG carriers. Huge amount of money is required to develop a gas reserve into LNG, therefore poses a great challenge to this technology of gas management, particularly in remote stranded gas sites [2]. However, a conventional LNG plant requires large feed gas volumes, in the range of 450–600 million standard cubic feet per day per LNG train. It is a great means of transportation of gas between countries and continents because liquefaction helps to reduce the volume of gas to about 600 times [31].

2.2. Gas to liquid (GTL)

This involves the conversion of natural gas or other forms of gaseous hydrocarbons into longer-chain hydrocarbons like diesel fuel or gasoline. This process produces diesel fuel with almost same energy density to the conventional diesel, but possesses a higher cetane number, and thereby permits better performance engine design [31]. This is achieved through the Fischer-Tropsch (F-T) process, which involves a chemical process whereby catalysts (like cobalt or iron) are used to synthesize complex hydrocarbons from simpler organic chemicals as shown in Fig. 7. The F-T process takes place between temperature ranges from 200 to 350 °C.

However, this technology is still at primordial stage and is capital intensive to manage. Another challenge it faces is the fact that the raw materials for conversion to commodity (silica sand, limestone) might prove difficult to import to site [41].

2.3. Pipeline to transport natural gas

This is a good means of transporting natural gas globally to the end users; and it is still in practice till date (responsible for about 75% of globally transported gas). This technology is also convenient and economical for onshore purposes [11].

Pipeline is the principal and most convenient method of transporting gas: either from an offshore location to onshore for processing or to interface with existing distribution grids. It is also used for transportation of export gas. Nevertheless, for offshore transport of natural gas, pipelines become challenging as the water depth and the transporting distance increase. It now becomes important to state that distance determines the economics of gas

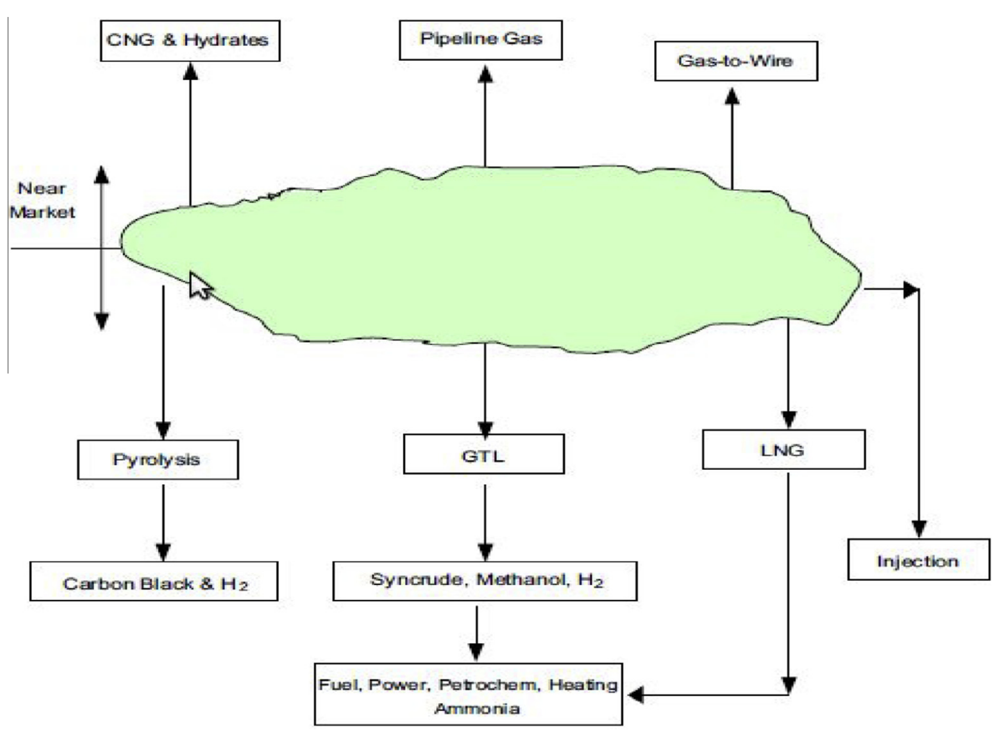

Fig. 6. Natural gas transport and development alternatives [31].

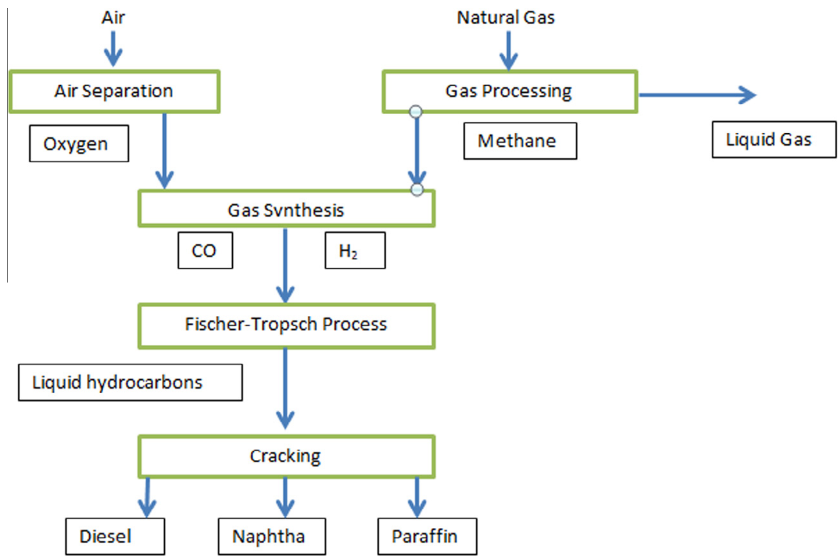

Fig. 7. A simplified GTL F-T Process (Adapted from [41]).

transportation [13]. An application of this technology is the West African Gas (WAGP), which has a capacity of 400 standard cubic feet per day and supplies gas for electricity generation to Benin Republic, Togo and Ghana from Nigeria [30].

However, these technologies are also facing some certain shortfall like vulnerability to sabotage, faces difficulty due to political boundaries and there is also the issue of gas not being readily stored.

2.4. Re-injection or recycle of natural gas

This is often applied offshore in order to boost oil recovery by maintaining reservoir pressure and simultaneously reduce or eliminate the need for gas transportation facilities [20]. It is often used in cases where investment in processing or export infrastructure would render the prospect uneconomical. This is still an attractive option for small volumes of associated gas aimed at utilizing small volumes of gas, which previously were flared because of the relatively small volume produced. However, for reservoirs with substantial gas reserves, re-injection is often considered uneconomical. It should be mentioned that water injection is the commonly used technique to boost oil recovery. However gas re-injection or recycling is a viable alternative to gas flaring. A typical gas re-injection process is shown in Fig. 8.

2.5. Electricity generation from natural gas

The gas to electricity technology involves use of gas as source of fuel for generation of electricity through a turbine [16]. This technology could be achieved through two major ways namely, combined heat and power (CHP) and combined cycle gas turbine (CCGT). CHP entails capturing and re-using of heat that is produced during electricity production. According to Marcecki [25], a CHP system deals with the concurrent cogeneration of electrical and heat energy in the form of low-pressure steam or hot water. A research by Pilavachi [37] stated that the CHP technology is characterised by the prime movers, which are devices that could convert heat energy into mechanical energy; engines that could be operated with gas, bio, diesel or bio-diesel; turbines, that could be operated with gas, fuel, steam, combined gas and steam system; or fuel cells, that could be operated with fuels obtained from natural gas.

A schematic process that shows the processes from gas production to gas being used as fuel to power a turbine and finally the production of energy is shown in Fig. 9.

The CCGT is a form of energy generation technology that combines gas-fired turbine of 100 or more Mega Watts (MW) capacities and a steam turbine [40]. Electricity is generated by a gas turbine and the resulting waste heat is converted to steam, which is subsequently utilised for generation of extra electricity. This is supported with the fact that heat is produced as a necessary by-product of power production [35]; thereby same heat is converted to steam and used to produce extra energy. Because the gas turbine operates at higher temperature, it labelled the 'topping cycle', whereas the steam turbine is known as 'bottoming cycle' as it operates at a lower temperature [22].

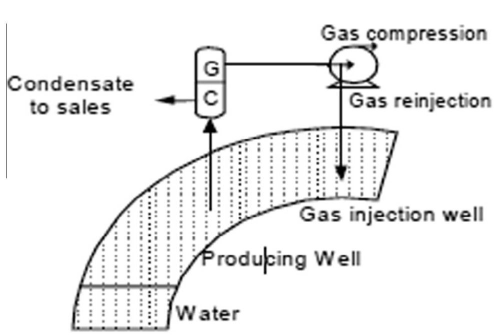

Fig. 8. Schematics of gas re-injection process [20].

3. Research method

In this study, a case study approach was used for two organisations – one from the oil and gas sector, and the other from the electricity generation sector in a developing country (Nigeria). For ethical reasons, the organisations are identified as Gas Company and Electric Company respectively.

The Gas Company is a gas production and distribution organisation which operates in Nigeria and has staff strength of over 300 employees. It has a gas production site that comprises 7 gas production wells that are responsible for the production of gas. It produces 7.2 million cubic meters of gas per day. It also consists of the Afam Field Manifold with five incoming 8-inch flowlines from the Afam wells. It also has one 12-inch 11 km bulkline from the Afam

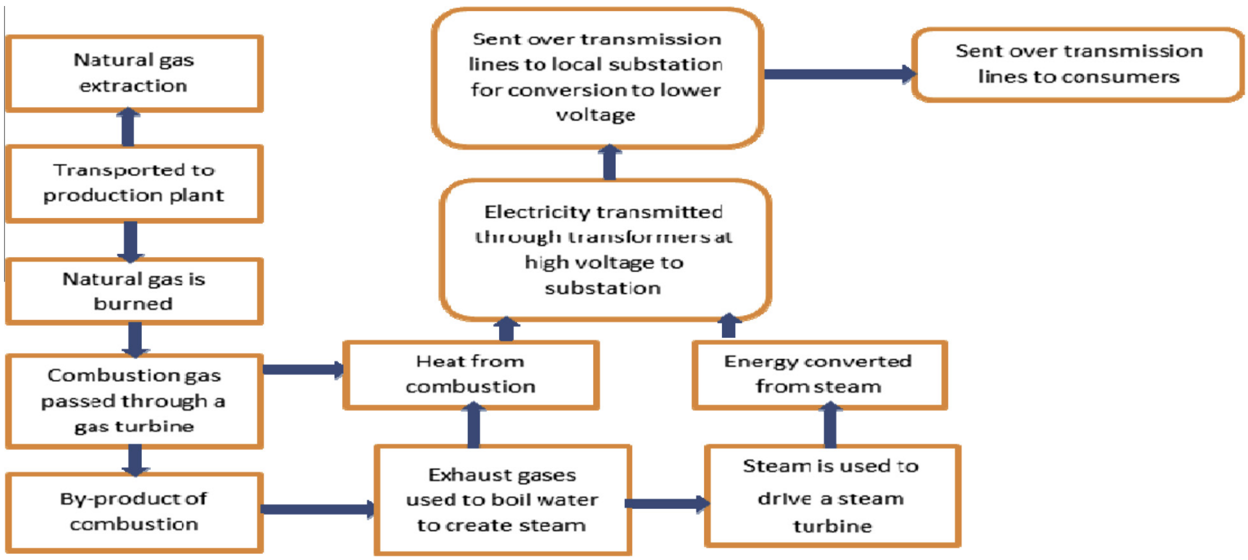

Fig. 9. Simple flow chart for conversion of gas-to-energy (Adapted from Long, 2001).

Field Manifold to the Gas Plant, as well as various other gas and condensate pipelines and flowlines of diameters from 4-inch to 16-inch with lengths from 1.2 up to about 12 km.

The gas produced is distributed to two different power stations for electricity generation. During processing, gas enters the train at 100 bars; but later reduces to about 60 bar to enable for onward delivery to the Electric Company. Consequently, gas from various wells are collected and channelled to the plant through pipelines for generation of electricity.

Structured interviews were conducted on three principal personnel from the Gas Company (operations supervisor, production manager and field manager). These interviews provided the study with specific and essential operations in the process of gas production, utilisation, and flaring. The study also had access to documents from the Gas Company which provided vital information that supported the outcome of this paper. From the company's documents, the daily quantities of gas produced, distributed to users as well as controllably flared were systematically collected, and these revealed that a total of 7.2 million cubic meters (MCM) of gas was produced daily on site. Out of the daily production, 6.6 MCM is utilised and 0.6 MCM is flared, signifying a flare percentage of 8.33%.

The Electric Company is the second case study and was chosen because it receives gas from the Gas Company for its electricity generation. It is one of the power stations in Nigeria and has about 400 employees working on different work-shifts over the clock. There are about 200 employees in the administrative department, 70 employees in operations department, 50 members of staff in maintenance department, and 20 staff each in store keeping, technical services and civil departments and casual workers.

The Electric Company has a total of 20 units of gas turbine of varying capacities. However, only one turbine with a capacity of 65 MW was functional, while the rest are either awaiting rehabilitation or have been decommissioned. Gas is supplied through pipelines to the Electric Company from the Gas Company which is about 2 km away. The gas is supplied through pipelines where pressure is reduced from 100 bars to 60 bars before being transferred/delivery to the Electric Company for generation of electricity.

Data were collected through structured interviews which were conducted on four principal personnel from the organisation. The plant manager, who is responsible for all the activities in the Power Station, assisted this study by providing relevant information such as the units of electricity produced and gas utilised, he also assisted in identifying the challenges faced in the power station; while the Head of Electricals provided information on electricity tariffs for end-users. The Head of Mechanical provided the needed information about the state of turbines such as capacities and outputs. The Shift Supervisor provided information on personnel logistics.

Table 2
Primary performance parameters for GT13E2 [4].

Fuel	Natural gas
Frequency	50 Hz
Gross electricity output	150 MW
Gross electricity efficiency	36.4%
Thermal efficiency	36%
Turbine speed	3000 rpm
Fuel gas temperature	31 °C

To successfully evaluate the economics of gas to wire technology for management of gas flare, a comprehensive estimated capital investment data was provided as shown in Table 7. The study calculated the cost of gas turbine which bears the greatest sum of the capital investment; we also estimated the cost of installation of the equipment. Furthermore, the cost of royalty to the host community of the power station was inputted. Consequently, the estimated income and return cost statement was provided as shown in Table 8. Prior to the economic analysis, this study made some economic assumptions as fully stated in Section 4.5, and reference was made on some economic equations for calculation of some variables as recommended by Peter and Timmerhaus [36] for plant design and economics for chemical engineers.

An economic evaluation for gas to wire was carried out using the ALSTOM GT13E2 gas turbine and its primary performance parameters are shown in Table 2. In total, this study provided estimation based on 50 units of gas turbine of 150 MW capacity each and this amounted to a total of 7500 MW of electricity generation in Nigeria. A unit of ALSTOM GT13E2 consumes a total of 0.93 million cubic meters (MCM) of gas per day and generates 150 MW of electricity, as identified from a power station in Nigeria during data collection.

4. Results and discussion

This section clearly identifies the outcomes from the case studies. These include quantity of gas produced, utilised and flared. This section also assessed the economics of GTW technology for gas flare management.

4.1. Quantity of gas produced in the gas company and utilised by the electric and gas utility companies

The quantity of gas produced by the Gas Company depends on the demand from customers (Electric Company and Gas Utility Company). Typically, the gas plant produces 7.2 million cubic meters per day (mcm/d): 3.0 MCM/day is supplied to Electric Company; while Gas Utility Company is supplied with 3.6 MCM/day. The remainder is flared (see Table 3). However, when the demand from the customers is less, the production is reduced to minimise waste (flaring).

4.2. Gas flaring process in the gas company

Minimal amount of gas flaring takes place occasionally in this particular gas plant. Results collected show that 8.33% of the total gas produced is flared; although this does not tell the whole gas flaring situation in Nigeria because Nigeria burns over 18 billion cubic meters annually. Interview data from the operations supervisor, the production manager and the field manager from the Gas Company show that daily flare rate in this company could be higher due to the following reasons:

- Reduction in demand by customers: Whenever there is a sudden trip (reduction in consumption) from customers, it brings about excessive pressure to the inlet valve. To avoid disaster or rather for safety reasons, the excess gas is channelled to the flare stack.
- Plant shutdown: This could either be in the form of planned and un-planned (also known as emergency shutdown) shutdowns. Unplanned shutdown happens due to loss of control or emergency situations like fire outbreak in the facility. In such a situation, there are measures to keep the gas plant safe, which involve instant shutting down of the plant which automatically involves gas flare. There could also be a case of process upset – high level of vessels will shut down thereby leading to chain shut down. Planned shutdown is a type of shut-down that is pre-planned and arranged. It could last for about 1–2 weeks. In this situation, the gas is channelled to the stack and lost through flaring.
- Separation of condensate: During separation of condensate from gas, there is need to stabilize the liquid. This leads to the gas being flashed off. So in the absence of a flash-gas compressor, more gas is flared.
- Loss of electricity power: This is an indirect reason for gas flaring in the plant. This is as a result of power failure or lack of use of gas to generate electricity by their customers. During routine maintenance or unplanned maintenance in the power plants, there would be minimal or no generation of electricity and this signifies that all or some of the turbines might not be operational. In this situation, the excessive gas in the plant is channelled to the gas stack for flaring.
- Plant overhaul: During total maintenance of the site/gas plant, gas is flared.

Table 3
Volume of gas produced, utilised and flared from the Gas Company.

Total amount of gas produced (MCM/day)		7.2
Quantity used (mcm/d)	Electric Company	3.0
	Gas utility Company	3.6
Quantity flared by Gas Company (mcm/d)		0.6

4.3. Gas turbine and electricity production in Electricity Company

The study carried out in the Electric Company shows the daily gas use by gas turbine units of certain capacities, as well as the amount of electricity produced by the power station during a certain period of time. Table 4 shows a breakdown of gas consumption and electricity generation from the turbines over a ten year period.

In 2003, 713,770,984.70 m^3 of gas which signifies the highest amount of gas was consumed, and also the highest electricity was generated (2,090,548.30 MWh). Electricity generated as well as gas consumed were the lowest in 2010 (95,947.40 MWh and 25,957,142.27 m^3 respectively). It appears that the major determinant for energy generated in a particular year was the number of functional gas turbines; this is because in the year 2010, there was just one functional gas turbine in the power plant which affected the total electricity generated.

In 2011, the Power Holding Company of Nigeria (PHCN) – the body that governs the use of electricity in Nigeria had an installed capacity of 6904.6 MW of electricity, and an available capacity of 3358 MW [9]. The significance is that just about 49% of the installed capacity is actually available. Also the three major sources of fuel for electricity generation for the national grid were natural gas, hydropower, and crude oil. Overall, natural gas contributes the highest with about 39.8%, while hydro energy and crude oil contribute 35.6% and 24.8% respectively [23]. Table 5 highlights the general conditions of the gas turbines in the Electric Company. 12 out of 20 units of gas turbine in the power station are completely written off and not functional; while 7 units fault ranging from mechanical damage on the compressor, damage on the turbine blades due to severe and constant exposure to high temperature, or corrosion of the compressor due to exposure to violent corrosive conditions. Also some of the turbines lack necessary spare parts for maintenance.

If all turbines were in good working condition and produced at maximum capacity, the expected electricity output from this power station will be 700 MWh. However, this study shows a daily production of 65 MWh which shows under performance.

4.4. Nigeria's estimated electricity need and actual availability

Electricity generation in Nigeria for the past 40 years has three major sources namely, gas-fired, hydroelectric and coal-fired [28]. The Power Holding Company of Nigeria (PHCN) is solely responsible for distributing electricity from the national grid to end-users in Nigeria and receives support for electricity generation from the Independent Power Producers (IPPs). In total, the PHCN therefore has 12 different power stations (although 2 are currently non-functional), out of which 9 are thermal, while 3 are from hydropower. Table 6 shows locations of the power stations in Nigeria (both functional and non-functional), with installed capacities as well as the number of units associated with each. Overall, PHCN electricity system currently comprises:

1. Seven thermal and three hydropower generating stations with a total daily installed capacity of 6904.6 MW, of which 3358 MW is available [3].
2. A radial transmission grid (330 kV and 132 kV) that is owned and managed by the Transmission Company of Nigeria (TCN).
3. Eleven distribution companies (33 kV and below).

Nigeria's daily electricity demand is estimated at 12,000 MWh, and PHCN has a total installed daily capacity of 6904.6 MW, of which 3358 MWh is produced at peak operation; while the Independent Power Producers (IPPs) generate 1000 MWh. The combined generation contributes 36.32% of the needed energy

Table 4
Electric Company energy generation and gas consumed from 2001 to 2012 [33].

Year	Available turbines	Total capacity (MW)	Energy generated (MWh)	Quantity of gas consumed (m^3)
2001	2	180	340,194.90	150,654,602.87
2002	2	105	184,672.10	967,598.27
2003	4	420	2,090,548.30	713,770,984.70
2004	4	420	1,247,813.10	449,833,371.00
2005	4	420	1,838,866.90	635,663,342.81
2006	4	420	1,864,110.30	664,138,805.91
2007	4	420	1,393,932.40	476,226,077.87
2008	2	180	305,340.00	127,526,576.25
2009	2	180	151,859.00	61,096,500.11
2010	1	105	95,947.40	25,957,142.27
2011	2	180	391,577.00	122,592,616.77
2012	2	180	497,885.20	204,378,866.54

Table 5
General conditions of existing gas turbines in the Electric Company.

Total unit of turbines	Decommissioned turbines	Turbines awaiting rehabilitation	Functional turbines	Capacity of turbine	
20	12	7	1	Installed (987.2 MW)	Produced (65 MWh)

Table 6
Generating plants/grid stations in Nigeria [3].

Site	Type	Installed capacity (MW)	Available capacity (MW)	No. of units
Afam	Thermal	987.2	65	20
Delta	Thermal	900	300	20
Egbin	Thermal	1320	1100	6
Geregu	Thermal	414	276	3
Olorumsogo	Thermal	304	76	–
Omotosho	Thermal	304	76	–
Sapele	Thermal	1020	90	10
Jebba	Hydro	540	450	6
Kainji	Hydro	760	480	12
Shiroro	Hydro	600	450	6
Orji River	Thermal	60	N/A	4
Calabar	Thermal	6.6	N/A	N/A
Total		6904.6	3358	

Table 7
Estimated capital investment statement.

Description	Cost (£)
Equipment (50 units of gas turbine)	1,051,575,000 (140.210/kW)
Piping and installation of equipment	360,900,000
Royalty to community	100,000
Working cost/maintenance	230,610,000/year
Total capital investment	1,643,185,000

capacity for the country. This is therefore an urgent need for improved electricity generation.

According to Ahmed et al. [1], about 40 percent of the Nigerian population has access to electricity, of which the majority are concentrated in the urban areas. This therefore shows that over 95 million people living in Nigeria (which represent about 60% of the population) do not have access to electricity, unless they provide electricity for themselves through the use of personal electricity generators. Fig. 10 shows the proportion of existing gas turbines needed in Nigeria (as proposed by this study) that could suffice for electricity generation and distribution in Nigeria. Overall, 20 units of gas turbine are in use across various power stations in Nigeria, while extra 60 units of gas turbines (at a capacity of 150 MW per unit) are required to augment the electricity production in Nigeria, assuming this technology was the only source of electricity generation in Nigeria. Fig. 11 presents the electricity production sources in Nigeria, and highlights the additional electricity needed to satisfy the need.

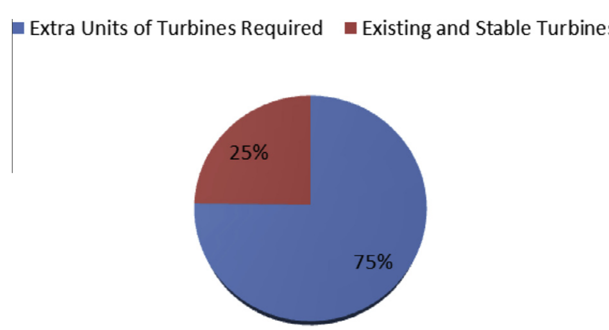

Fig. 10. Gas turbine scenario in Nigerian power stations.

Following the findings and discussions from both case studies, the following section provides a cost and effect analysis of the economics of GTW technology for gas flare management.

4.5. Economic assessment of gas to wire

- The economic evaluation is based on the assumption that the availability and consistency of the gas turbines (in terms of being in good working condition) are 100% throughout the year (i.e., the plants operate for 365 days of the year).
- We further assumed that the units of gas turbine (50 units) function at full power capacity, which is 150 MW x 50 units, and selling all the produced electricity to the national grid.

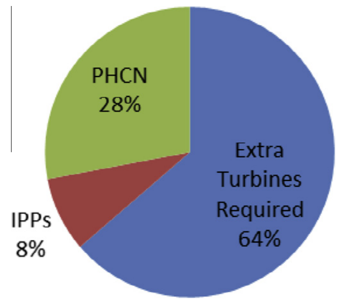

Fig. 11. State of electricity production in Nigeria.

- It is also worth reiterating that this economic assessment is based on 50 units of gas turbine.
- Calculations for break-even point capacity (B.E.P), product cost for plant, yearly income in B.E.P capacity, total yearly income, gross profit, net profit and rate of return (ROR) were done using Eqs. (1)–(7) [36].

$$\text{Product cost for sale} \times \text{B.E.P capacity} = \text{product cost for plant} \times \text{B.E.P capacity} + \text{fixed charge} \quad (1)$$

$$\text{Product cost for plant} = \text{Direct Production Cost} \div \text{Plant Capacity} \quad (2)$$

$$\text{Yearly income in B.E.P Capacity} = \text{Break-even point capacity} \times \text{product cost for sale} \quad (3)$$

$$\text{Total Yearly Income} = \text{Capacity of Unit per year x Product Cost for sale} \quad (4)$$

$$\text{Gross Profit} = \text{Total yearly income} - \text{Yearly income in B.E.P Capacity} \quad (5)$$

$$\text{Net Profit} = 0.7 \times \text{Gross Profit} \quad (6)$$

$$\text{ROR} = \text{Annual Profit} \div \text{Capital Investment} \times 100 \quad (7)$$

The product cost for sale is the retail cost of electricity per kWh. Total product cost for sale is the financial value of the all generated electricity, and this also represents the total yearly income. Product cost for plant is the cost of electricity generation per kWh. To determine the net profit, 30% corporate tax which operates in Nigeria is applied [42].

Table 7 represents a statement for the estimated capital for the generation of 7500 MW of electricity in Nigeria which is the total amount of electricity produced by 50 units of gas turbine; while Table 8 provides the estimated income and return statement. Larger bulk of the estimated capital investment is channelled towards purchase of units of gas turbine. This signifies that the lesser the units of gas turbine, the lower the capital investment. However, the reduction in units of turbine will create an impact on the estimated income because its leads to reduced electricity generation. It is worth mentioning that the calculation in this study does not include cost for spare parts replacement. This is because of the uncertainties that might be related to spare parts replacement such as cost variation and time for replacement which depends on breakdown of machine parts.

From Table 7, the units of gas turbine (turbine capacity) are significant on total capital investment because its cost is high. Therefore, a change in the number of units, either an increase or decrease will create a rise or fall respectively on the total capital investment.

Table 8
Estimated income and return cost statement.

Caption	Value (£)
Product cost for sale	£0.07/kwh
Total product cost for sale/year	4,599,000,000
Direct production cost	£459,900,000
Product cost for plant	£0.007/kWh
Total product cost for plant	£459,900,000
Fixed charges	£689,850,000/year
Break-even point capacity	10,950,000,000 kWh
Yearly income in B.E.P capacity	£766,500,000
Capacity of unit per year	65,700,000,000 kWh
Total yearly income	£4,599,000,000
Gross profit	3,832,500,000/year
Net profit	2,682,750,000/year
ROR	16.3%/year

The economic assessment has shown that GTW technology is a profitable means of gas flare management. This is linked to the income and return cost statement in Table 8 which shows an annual net profit of £2.68 billion with an investment rate of return of 16.3% annually.

5. Conclusions

This paper has presented the economics of employing gas to wire (GTW) technology to manage gas flare which has significantly contributed to world environmental and health challenges. The investigation determined the volume of gas produced, utilised and flared and the associated amount of electricity needed and produced, as well as economic cost of electricity in Nigeria. Based on the findings of this study, it may be inferred that electricity generation through GTW is a viable technology to achieve gas flare reduction, particularly in Nigeria. This assertion is based on the fact from the information and data collected from a gas production and flaring company and an electricity generation and distribution company with regards to gas production and flaring as well as electricity generation respectively in Nigeria. Subsequently, the identification that Nigeria needs about 12,000 MW of electricity daily, while it currently produces an insufficient amount of 3358 MW of electricity daily supports the justification as this GTW technology will be a sustainable means of flare gas utilisation/minimisation more than other technologies like GTL and LNG. Also, to further portray the justification of GTW technology for flare gas management Rahimpour et al. [38], identified that it is associated with high annual profit when compared with other technologies such as GTL and gas compression.

GTW technology requires installation of gas turbines in power station as a key step in the process. Although it is a huge project that requires financial investments, it can be established based on the findings that GTW application in Nigeria is economically viable and sustainable. Generation of 7500 MW of electricity in Nigeria with 50 units of gas turbine (ALSTOM GT13E2) would require an estimated capital investment of £1,643,185,000. Huge proportion of the capital is expected to be used in turbine acquisition but analysis shows that there is potentially net profit of £2.68 billion per year. The technology has demonstrated capacity of high rate of return of investment of 16.3%. Apart from being economically substantial, GTW technology would potentially bring a significant reduction on volume of gas flared annual in Nigeria. Such reduction would lead to more reduction in environmental impact.

Acknowledgements

The authors are grateful to the staff of Afam Power Station and Afam Gas Station, Nigeria, especially Engineer Paul C. Amara, Engineer Agha Ogbonna and Engineer Obinwanne Agugharam for their unreserved support during collection of data for the study. The contributions from Dr. Emeka Amalu are highly appreciated. Also, the authors acknowledge the support received from the University of Wolverhampton, United Kingdom.

References

[1] M.M. Ahmed, A.A. Bello, M.N. Idris, Natural gas utilization and the nigerian gas-to-liquid project; an opportunity to end gas flaring, Int. J. Emerg. Trends Eng. Dev. 2 (2) (2012) 240–256.

[2] K. Akachidike, Remote Stranded Gas-Challenges and Opportunities for Development: Proceedings of the 38th Annual Conference of NSChE, Effurun, Delta State, Nigeria, 2008.

[3] A.S. Aliyu, T.R. Ramli, A.S. Saleh, Nigeria electricity crisis: power generation capacity expansion and environmental ramifications, Energy 61 (2013) 354–367.

[4] ALSTOM Power, Plant Data Sheet for ALSTOM Gas Turbine GT13E2 within Open Cycle Plant in Port Harcourt, Nigeria. Part of Documentation from Case Study, 2010.

[5] O. Anomohanran, Determination of greenhouse gas emission resulting from gas flaring activities in Nigeria, Energy Policy 45 (2012) 666–670.

[6] A. Bahadori, Natural gas processing: overview of natural gas, Technol. Eng. Des. (2014) 1–22.

[7] R.D. Bowden, K.M. Newkirk, G.M. Rullo, Carbon dioxide and methane fluxes by a forest soil under laboratory-controlled moisture and temperature conditions, Soil Biol. Biochem. 30 (12) (1998) 1591–1597.

[8] British Petroleum, Statistical Review of World Energy, 2015. Available [Online] from <http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html> (viewed 07/01/2016).

[9] Bureau of Public Enterprises, Power generation (status and outlook); Presidential Tax Force on Power. Paper presented at the electric power Investors' Forum, In: Abuja, Nigeria on 14 January 2011, 2011. Available [Online] from <http//www.nigeriaelectricityprivatisation.com> (viewed on 2/2/14).

[10] Canadian Centre for Energy Information, Flaring, 2006. Available [Online] from <http://siteresources.worldbank.org/EXTGGFR/Resources/578068-1258067586081/FlaringQA.pdf>.

[11] A. Deshpande, M.J. Economides, CNG: An Alternative Transport for Natural Gas Instead of LNG, University of Houston, 2005.

[12] E.J. Dung, S.B. Leonard, T.D. Agusomu, The effect of gas flaring on crops in the Niger Delta, Nigeria, GeoJournal 73 (2008) 297–305.

[13] C. Durr, D. Coyle, D. Hill, S. Smith, LNG Technology for the Commercially Minded, Gastech, Bilbao, Spain, 2007.

[14] Energy Information Administration, Annual Energy Outlook 2004 with Projections to 2025, U.S. Department of Energy, 2004 (cited in Indriani).

[15] Energy Information Administration, U.S. Energy Information Adminstration. Country Analysis Brief Overview: Nigeria, 2013. Available [Online] from: <http://www.eia.gov/countries/country-data.cfm?fips¼NI> (viewed 05/07/14).

[16] M.F. Farina, Flare gas reduction – recent global and policy considerations, GE Energy Global Strat. Plan. (2010).

[17] K. Fielden, Fixing flaring, Chem. Eng.: Issue 892 (2015) 26–30.

[18] J.-B. Geng, Q. Ji, Multiple-perspective analysis of China's energy supply security, Energy 64 (2014) 541–550.

[19] D.N. Hewitt, W.T. Sturges, A. Noa, Global Atmospheric Chemical Changes, Chapman and Hall, New York, 1995.

[20] G. Indriani, Gas Flaring Reduction in the Indonesian Oil and Gas Sector – Technical and Economic Potential of Clean Development Mechanism (CDM) projects, 2005. Available [Online] from <http://ageconsearch.umn.edu/bitstream/26096/1/re050253.pdf> (viewed 12/04/2015).

[22] R. Kehlhofer, F. Hannemann, F. Stirnimann, B. Rukes, Simplified Flow Diagram of Combined Cycle. Combined-Cycle Gas and Steam Turbine Power Plants, 3rd ed., Penn Well Corporation, USA, 2009.

[23] J. Kennedy-Darling, N. Hoyt, K. Murao, A. Ross, The Energy Crisis of Nigeria An Overview and Implications for the Future, 2008.

[25] J. Marcecki, Combined Heat and Power Generating Systems, Peter Peregrinus Limited, London, 1988.

[26] Middle East Economic Survey, Top Five Gas Flaring Countries in 2010, 2012. Available (Online) from <http//www.mees.com/en/articles/3207-iraq-s-chalenges-on-its-path-towards-a-world-class-gas-industry> (viewed 23/03/2012).

[27] NLNG, Facts and Figures on NLNG, 2011. Available [Online] from <http://nigerialng.com/publications/facts%20&%20figures%20xxx.pdf> (viewed 21/09/12).

[28] E.O. Nwaichi, M.A. Uzazobona, Estimation of the CO_2 level due to gas flaring in the Niger Delta, J. Environ. Sci. 5 (6) (2011) 565–572.

[29] C.N. Nwankwo, D.O. Ogagarue, Effects of gas flaring on surface and ground waters in Delta state Nigeria, J. Geol. Min. Res. 3 (5) (2011) 131–136.

[30] E.O. Obanijesu, M.A. Waheed, S.R.A. Macaulay, West African Gas Pipeline (WAGP) Project: Associated Problems and Possible Remedies, 2008. Available [Online] from <https://www.researchgate.net/profile/Emmanuel_Obanijesu/publication/226621388_West_African_Gas_Pipeline_(WAGP)_Project_Associated_Problems_and_Possible_Remedies/links/54ae084d0cf24aca1c6f71e0.pdf> (viewed 15/01/2016).

[31] C.A. Odumugbo, Natural gas utilization in Nigeria: challenges and opportunities, J. Nat. Gas Sci. Eng. 2 (2010) 310–316.

[32] Oil and Gas Producers, Flaring and Venting in the Oil and Gas Exploration and Production Industry: An Overview of Purpose, Quantities, Issues, Practice and Trends. Report No 2, 79/288, 2000, Available [Online] from <http://www.ogp.org.uk/pubs/288.pdf> 28/10/2012.

[33] E. Ojijiagwo, C.F. Oduoza, The Economics of Gas Flaring in Oil and Gas Processing Environments: A Case Study of Electric Power Station in a Developing Country, in: 24th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM), San Antonio, Texas, USA, 2014.

[34] O.O.I. Orimoogunje, A.A. Ayanlade, T.A. Akintuolie, A.U. Odiong, Perception on effect of gas flaring on the environment, J. Environ. Earth Sci. 2 (4) (2010) 188–193.

[35] N. Petchers, Combined Heating, Cooling and Power Handbook: Technologies and Application, The Fairmont Press Inc., Lilburn, GA, 2003.

[36] M.S. Peters, K.D. Timmerhaus, Plant Design and Economics for Chemical Engineers, International Ed., McGraw-Hill, New York, USA, 1991.

[37] P.A. Pilavachi, Power generation with gas turbine systems and combined heat and power, Appl. Therm. Eng. 20 (2000) 1421–1429.

[38] M.R. Rahimpour, Z. Jamshidnejad, S.M. Jokar, G. Karimi, A. Ghorbani, A.H. Mohammadi, A comparative study of three methods for flare gas recovery of Asalooye gas refinery, J. Nat. Gas Sci. Eng. 4 (2012) 17–28.

[39] R. Rotty, First estimation of global flaring of natural gas, Atmos. Environ. 8 (1974) 681–686.

[40] M.S. Suomalainen, A. Arasto, S. Teir, S. Siitonen, Improving a pre-combustion CCS concept in gas turbine combined cycle for CHP production, Energy Procedia 37 (2013) 2327–2340.

[41] S. Thomas, R.A. Dawe, Review of ways to transport natural gas energy from countries which do not need the gas for domestic use, Energy 28 (2003) 1461–1477.

[42] Trading Economics, Nigeria Corporate Tax Rate, 2016. Available [Online] from <http://www.tradingeconomics.com/nigeria/corporate-tax-rate> (viewed 02/05/2016).